Outputs of Scientific and Engineering Research: Articles and Patents

The products of academic research include trained personnel and advances in knowledge. Trained personnel have been discussed in chapter 4 of this volume and earlier in this chapter. This section presents two sets of indicators of advances in knowledge: articles published in a set of the world's most influential refereed journals (see sidebar, "Data Sources for Article Outputs"), and patents awarded to U.S. universities and colleges.

While academic researchers contribute the bulk of all scientific and technical articles published in the United States, the focus in this section is considerably broader. It includes U.S. articles in all sectors, and total U.S. articles in the context of article outputs of the world's nations, as reflected in a set of major international scientific and technical journals whose contents are covered in the Institute of Scientific Information's (ISI) Science Citation Index (SCI) and Social Science Citation Index (SSCI).

The *output volume* of research—*article counts*—is one basic indicator of the degree to which different performers contribute to the world's production of research-based S&E knowledge. The outputs of different U.S. sectors—universities and colleges, industry, government, and nonprofit institutions—indicate these organizations' relative prominence in the United States overall and in particular S&E fields. The same indicator, aggregated by country, provides approximate information about the U.S. position in the global S&E enterprise and the emergence of centers of S&E activity.

Scientific *collaboration* in all fields increasingly crosses organizational and national boundaries. Articles with *multiple authors* in different venues or countries provide an indicator of the degree of collaboration across sectors and nations. Scientific collaboration has risen with the actions of governments to stimulate it, especially over the past decade. Cross-sectoral collaboration is viewed as a vehicle for moving research results toward practical application. International collaboration, often compelled by reasons of cost or scope of the issue, provides intellectual cross-fertilization and ready access to work done elsewhere.

The perceived *usefulness* of research results to further advancement of the state of knowledge is reflected in *citations*. Both domestic and international citation patterns will be examined. A related indicator, references to scientific and technical articles on patents, suggests the relatedness of the research to presumed practical application.

Data Sources for Article Outputs

The *article counts, coauthorship data,* and *citations* discussed in this section are based on scientific and engineering articles published in a stable set of about 5,000 of the world's most influential scientific and technical journals tracked since 1985 by the Institute of Scientific Information's (ISI) Science Citation Index (SCI) and Social Science Citation Index (SSCI). Fields in this database are determined by the classification of the journals in which articles appear; journals in turn are classified based on the patterns of their citations, as follows:

Field	Percent of journals
Clinical medicine	24
Biomedical research	11
Biological sciences	10
Chemistry	7
Physics	5
Earth and space sciences	5
Engineering and technology	8
Mathematics	3
Psychology	6
Social sciences	11
Other	10

For the first time, journals in psychology, the social sciences, and certain other applied social science fields are included in the analysis, to provide a fuller examination of all science and engineering fields. The "other" category includes ISI-covered journals in professional fields and health whose citation patterns indicate their strong links to the social sciences or psychology. Appendix table 6-48 lists the constituent subfields of the journals covered here.

The SCI and SSCI appear to give reasonably good coverage of a core set of internationally recognized scientific journals, albeit with some English-language bias. Journals of regional or local importance are not necessarily well covered, which may be salient for the engineering and technology, psychology, social sciences, and "other" categories, as well as for nations with a small or applied science base.

Articles are attributed to countries and sectors by their authors' institutional affiliations at time of authorship. Thus, coauthorship as used here refers to corporate coauthorship: a paper is considered coauthored only if its authors have different institutional affiliations. The same applies to cross-sectoral or international collaborations. For example, a paper written by an American temporarily residing in Britain with someone at her U.S. home institution is counted as internationally coauthored, thus overstating the extent of such collaborations. Likewise, an article written by a British citizen temporarily located at a U.S. university with a U.S. colleague would not be counted as internationally coauthored, thus understating the count.

All data presented here derive from the Science Indicators database prepared for NSF by CHI Research, Inc. The database *excludes* all letters to the editor, news pieces, editorials, and other content whose central purpose is not the presentation or discussion of scientific data, theory, methods, apparatus, or experiments.

Finally, *patents issued to U.S. universities* will be examined. They provide another indicator of the *perceived utility* of the underlying research, with trends in their volume and nature indicating the universities' interest in seeking commercialization of its results.

U.S. Articles: Counts, Collaboration, and Citations

The complexity and breadth of a nation's science and engineering infrastructure is frequently described in terms of the financial resources it consumes and its personnel base. Article outputs provide another indicator that is particularly well suited to the mapping of the basic and applied research activities carried out in the United States—that is, activities for which articles are often the prime output. What is the contribution of scientists and engineers in the different sectors to the production of U.S. research articles, and in what fields?

All U.S. sectors contribute to the published, refereed science and technology (S&T) literature, albeit in different proportions, with academia providing the bulk of the article output. During 1995–97, an annual average of 173,200 articles were published by U.S. authors in a set of scientific and technical journals covered by the Science and Social Science Citation Indexes since 1985. (See appendix table 6-49.) Over the period, academic researchers contributed almost three-fourths of the total output; industry, the Federal Government, and the nonprofit sector (mainly health-related organizations publishing in life sciences fields) contributed 7–8 percent each. The output of federally funded R&D centers (FFRDCs) added another 3 percent to the total. (See figure 6-30 and appendix table 6-50.)

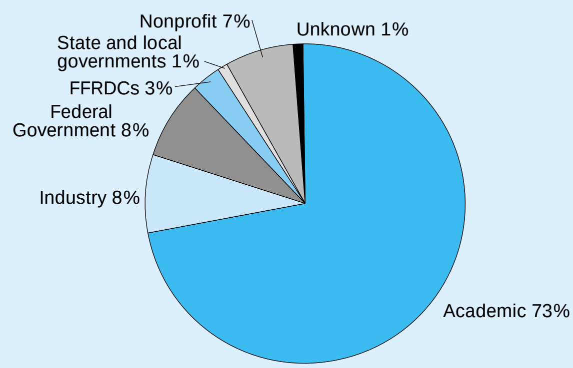
More than half of this U.S. portfolio of scientific and technical research articles—55 percent—covered subjects in the life sciences; another 26 percent dealt with physical sciences, earth and space sciences, and mathematics; 6 percent with engineering and technology; and the remainder with the social and behavioral sciences, including health and professional fields with close ties (based on citations) to the latter two fields. (See figure 6-31.)

Different sectors have different relative emphases. In the portfolios of academia, government, and nonprofit institutions, articles in life sciences fields are prominent, especially in clinical medicine and biomedical research. Industry articles focus on clinical medicine, physics, chemistry, and engineering and technology, with a growing emphasis on the life sciences. FFRDC articles focus on physics, chemistry, earth and space sciences, and engineering and technology. (See appendix tables 6-49 and 6-50.)

Viewed across all performer sectors, little change is evident in the field distribution of these articles—earth and space science registered marginal gains, as did biomedical research and clinical medicine, while biology lost some ground. Likewise, the overall contribution of the different sectors has changed little, except for a marginal percentage-point gain of academia offsetting a marginal decline in industry's share. However, over the 1988–97 decade, some changes in the field mix within specific sectors are worthy of note:

- Among *industry articles*, the number of physics articles declined by half during the 1990s, causing their share to decline steeply, from 21 percent a decade ago to less than 15 percent. Article volume in clinical medicine and biomedical research rose by 20 percent, bringing about share gains from 18 to 24 percent and from 10 to 13 percent, respectively. These numbers clearly indicate a shift in publishing activity (though not necessarily R&D—see chapter 2) from traditional physical-sciences- and engineering-oriented industry segments toward those in pharmaceuticals and other life-science-related areas. (See appendix table 6-49.)

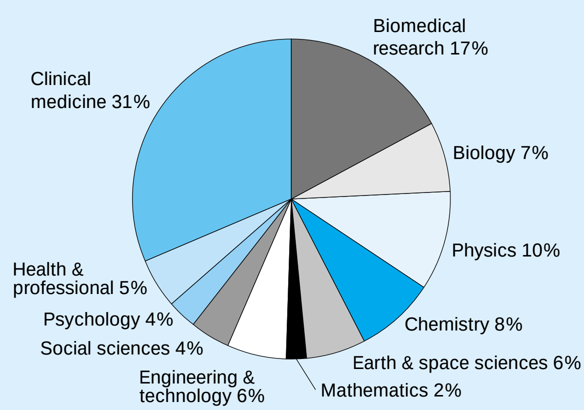
Figure 6-30.
Distribution of U.S. scientific and technical articles, by sector: 1995–97



FFRDC = Federally Funded Research and Development Center

See appendix table 6-50. *Science & Engineering Indicators – 2000*

Figure 6-31.
Distribution of U.S. scientific and technical articles, by field: 1995–97



See appendix table 6-49. *Science & Engineering Indicators – 2000*

- ♦ Changes in *academia's portfolio* were more gradual, showing gains of 1 percentage point each in physics, earth and space sciences, and biomedical research publications, with declines in biology and the social sciences. (See appendix table 6-49.)

- ♦ The *Federal Government's output* showed mixed trends. The relative balance of in-house articles shifted modestly toward physics and earth and space sciences, with some decline in clinical medicine and biology. However, among articles from university-affiliated FFRDCs, the share of physics papers fell by nearly 3 percentage points, accompanied by a growing share for earth and space sciences articles. (See appendix table 6-49.)

Scientific Collaboration

Developments in science and engineering have led to broader collaboration among researchers. As the scale, cost, and complexity of attacking many problems have increased, research teams have become common, changing the structure of the research. Single-investigator work, as evidenced by single-author publications, is in decline in virtually all fields. The Federal Government has long sought to stimulate this trend, for example, by promoting collaboration across sectors: for example, industry-university or FFRDC-industry activities. (See chapter 2.) Such cross-sector collaboration is seen as enriching the perspectives of researchers in both settings, and as a means for more efficiently channeling research results toward practical applications.

Two trends predominate in the collaborative activities of U.S. researchers:

- ♦ strong cross-sectoral collaboration, and

- ♦ increasing international collaboration.

The proportion of U.S. scientific and technical articles with multiple institutional authors has continued to rise. In 1997, 57 percent of all S&E articles had multiple authors, up from 49 percent a decade earlier. This resulted from a falling number of U.S. single-author articles, accompanied by a rise in the number of multi-author articles. This general pattern held for all but mathematics, psychology, and the social sciences, where falling single-author output was accompanied by static counts of multi-author papers. (See appendix table 6-51.) Coauthorship was highest in clinical medicine, biomedical research, earth and space sciences, and physics (ranging from 59 to 66 percent), lowest in the social and behavioral sciences and chemistry (from 36 to 44 percent).

The bulk of the increase in corporate[60] coauthorship of U.S. articles reflected rising international collaboration. By the mid-1990s, nearly one article in five—18 percent—had at least one non-U.S. author, up from 12 percent at the beginning of the decade. Physics, earth and space sciences, and mathematics had the highest rates of international coauthorship, ranging from 27 to 30 percent of all U.S. articles. International collaboration rates were much lower in the social and behavioral sciences—9–10 percent. (See appendix table 6-51.)

Academia was at the center of cross-sector collaborations in every sector and field. Coauthorship rates with academia—the percentage of a sector's coauthored papers with an academic collaborator—were above 70 percent for the Federal Government, university-managed FFRDCs, and nonprofit institutions. For other sectors, they ranged from 59 percent for industry-managed FFRDCs to 66 percent for industry itself. In mathematics, 80–90 percent of cross-sector collaborations were with authors in higher education institutions, underlining the key role of academia in mathematics research, where 93 percent of U.S. articles in that field are published. (See appendix table 6-52.)

Other collaborative patterns vary by field, depending on different sectors' relative strengths and foci. For the industry sector, joint work with the Federal Government was prominent in earth and space science, as was collaboration with nonprofit authors in clinical medicine and biomedical research. For the Federal Government, industry collaboration in physics, chemistry, earth and space sciences, and engineering and technology was prominent, as were university-managed FFRDCs in earth and space sciences. The nonprofit sector's collaborations focused heavily on academia and the Federal Government, except in engineering and technology, where nearly one-third of cross-sector articles were coauthored with industry researchers. (See appendix table 6-52.)

Academic scientists had strong collaborative ties with industry in physics, chemistry, mathematics, and engineering and technology (ranging from 31 to 55 percent of academic cross-sector collaborations in these fields). More than half of academia's cross-sector articles in biology had Federal Government authors, while collaboration with nonprofit institutions was heavy in clinical medicine and biomedical research (44 and 38 percent, respectively), in the social and behavioral sciences (48 and 42 percent, respectively), and in the health and professional fields (37 percent). In the physical sciences, academic collaboration with authors in university-managed FFRDCs was pronounced. (See appendix table 6-52.)

Citations

In their articles, scientists cite prior research on which their own work builds. These citations, aggregated by field and sector, provide a rough indicator of the use of these articles by researchers working in different sectors.

The distribution of citations to U.S. scientific and technical articles largely—but not entirely—reflects that of the articles themselves, with the bulk of citations going to academic papers. Citation to same-sector articles generally exceeded sector shares, only somewhat for the dominant academic publishing sector, three- to fourfold for most other sectors, tenfold for articles from FFRDCs. The share of citations from each of these sectors to academic publications grew over the decade. (See appendix table 6-53.)

The academic sector received 72 percent of all 1994–97 U.S. citations. Its share of citations in chemistry, engineering

[60]Throughout the chapter, coauthorship refers to *corporate* coauthorship: that is, joint authors with different institutional affiliations. See sidebar, "Data Sources for Article Outputs," above.

and technology, and the social sciences exceeded the sector's share of U.S. articles in these fields.[61] Differences between academic article and citation shares in other fields were generally minor. For other sectors and fields, the relative citation volume was generally what would be expected on the basis of output shares. Exceptions were higher-than-expected biomedical research citations to nonprofit sector publications, and lower-than-expected citation frequency of industrial articles in chemistry and engineering and technology. (See appendix tables 6-50 and 6-53.)

Care must be taken to avoid misinterpretation of these differences: they are not indicators of quality differentials. In ongoing research, basic research will tend to be cited with relatively greater frequency than applied research. To the extent that industry articles tend to be less basic than those from academia, the comparison of article output and citation shares is a very rough one indeed.

Linkages Among Disciplines

Research on many challenging scientific problems draws on knowledge and perspectives of a multitude of disciplines and specialties. Citations in scientific and technical articles that cross disciplinary boundaries are one indicator of the multidisciplinary nature of the conduct of research. Of course, frequency of citations only hints at how essential a particular piece of work was to the research being reported. The indicator used here is relatively weak, because of its reliance on a journals-based field classification. Data for other, stronger indicators of multidisciplinary research activities are not readily available: collaboration of researchers across disciplinary boundaries, multidisciplinary centers, and major multidisciplinary projects—for example, global climate research—lack readily available representative data. Nevertheless, cross-disciplinary citations do provide an insight into connections among major fields and fine fields. They demonstrate the relevance to progress in a given field of advances in a range of other fields.

Citations in U.S. articles published in 1997 were aggregated by field.[62] There were approximately 1.3 million such references: 71 percent to the life sciences; 22 percent to mathematics, the physical, and earth and space sciences combined; 5 percent to the social and behavioral sciences and related health and professional fields combined, and just under 2 percent to engineering. (See appendix table 6-54.)

The distribution of citations across broad fields shows the expected concentration of references to articles in the same broad field. Biology and engineering have the lowest rates of self-citation (in this broad-field sense): 62 percent each. Physics and the earth and space sciences have the highest rates: 82 and 83 percent, respectively. Citations in life sciences articles—biology, biomedical research, and clinical medicine—were particularly heavily focused on these three fields: 92 percent of all citations in biology, 97 percent of those in biomedical research, and 98 percent of those in clinical medicine were to articles in the life sciences. A greater proportion of citations in the other sciences and engineering focus on the life sciences fields than vice versa. (See appendix table 6-54.)

Examination of fine fields generally underscores the tight connection among the life science fields, but also reveals the strength of their connections which extend into other fields. For example, one-fifth of all citations in marine and hydrobiology are to fields outside the life sciences, particularly to earth and space sciences and physical sciences. In clinical medicine, nearly one-fifth of the citations found in articles on addictive diseases are to articles in the behavioral and social sciences and related health and professional fields. Especially strong links to fields outside the life sciences also characterize agricultural and food sciences, ecology, biomedical engineering, biophysics, microscopy, pharmacy, and environmental and occupational health.

Citations for the physical and earth and space sciences show strong links to other physical science fields, engineering, and especially to biomedical research. The social and behavioral sciences are linked among themselves but also to specific areas in clinical medicine, biomedical research, and biology. (See appendix table 6-54.)

International Article Production: Counts, Collaboration, and Citations

The world's key scientific and technical journals exercise a degree of quality control by requiring articles submitted for publication to undergo peer review. Thus, the volume of different countries' articles in these peer-reviewed journals is a rough indicator of their level of participation in the international S&T arena. In addition, the distribution of their articles across fields reveals national research foci.[63]

Worldwide publication of scientific and technical articles averaged about 515,700 per year during 1995–97, a 12 percent increase over the 1986–88 period.[64] The largest category, clinical medicine, accounted for 29 percent of the total, about the same as for physics and chemistry combined; biomedical research (15 percent), biology, and engineering and technology (7 percent each) accounted for the bulk of the remainder. (See figure 6-32 and appendix table 6-55.) Note that this field distribution differs from that of the United States shown in figure 6-31—it is lower in the life sciences areas and distinctly higher in physics and chemistry.

Over the 1995–97 period, five nations produced approximately 62 percent of the articles published in the 1985 SCI set of journals: the United States (34 percent), Japan (9 per-

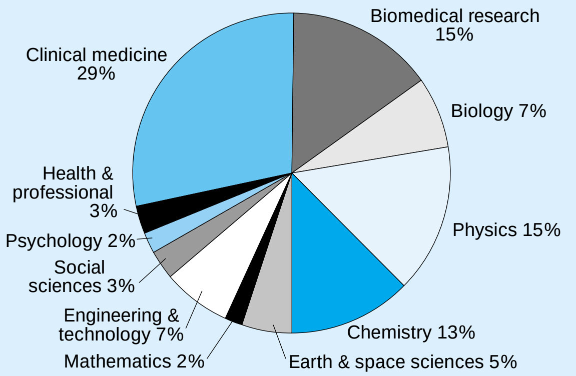
[61]The comparison made here is based on the 1989–94 publications data in appendix table 6-50.

[62]Specifically, citations in 1997 U.S. articles covered in the ISI Science and Social Science Citation Indexes to articles published in 1993–95.

[63]The numbers reported here are based on the 1985 ISI set of core journals, to facilitate comparisons over the countries. Counts are fractional: an article with multinational authors is assigned to the participating countries in proportion to their share of authors. Percentages reflect fractional counts. This set of influential world S&T journals has some English language bias but is widely used around the world. See for example Organization of American States (1997) and European Commission (1997). Also see sidebar, "Data Sources for Article Outputs" in this chapter.

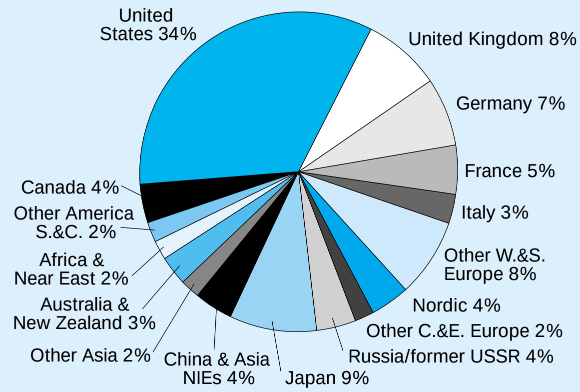
[64]This is a minimum estimate: an expanded 1991 journal set yields a slightly higher growth rate for the 1990s.

Figure 6-32.
Distribution of the world's scientific and technical articles, by field: 1995–97



See appendix table 6-55. *Science & Engineering Indicators – 2000*

Figure 6-33.
Distribution of the world's scientific and technical articles in major journals, by region/country: 1995–97



NIE = newly industrialized Asian economics

See appendix table 6-56. *Science & Engineering Indicators – 2000*

cent), the United Kingdom (8 percent), Germany (7 percent), and France (5 percent).[65] No other country's output reached 5 percent of the total. (See figure 6-33.) These countries possess relatively large and wealthy economies, extensive scientific and technical infrastructure, and large pools of scientists and engineers,[66] which undergird their continuing large share of the world's scientific and technical publications (as captured in the ISI database). Nevertheless, the five countries' collective proportion of the world's article output declined slightly over the past decade, from 64 percent in 1986–88 (and from 38 percent for the United States). This trend reflected the development or strengthening of scientific capabilities in several countries and world regions—in Asia and Southern Europe—following the end of the Cold War. (See appendix table 6-56.)

Over the last decade, the article share of Western and Southern European countries rose from 31 to 35 percent, reaching a level similar to that of the United States. It is likely that these gains reflect, at least in part, these nations' concerted policies to strengthen the science base in individual countries and across Europe as a whole.[67] The article volume of the Central European states as a group—Bulgaria, the Czech Republic, Hungary, Poland, Romania, and Slovakia—declined somewhat through the early 1990s, but by 1995–97 it had rebounded to 10,400 articles, slightly above its 1986–88 level. In contrast, the output for the nations of the former Soviet Union declined during the 1990s, dropping from about 31,200 in 1986–88 to 26,600 in 1992–94 and further to 22,200 in the 1995–97 period. This numerical decrease led to a decline in world share from 7 to 4 percent; especially sharp drops occurred in clinical medicine and biomedical research. The ongoing decline in these countries' output during the 1990s points to continuing difficulties that affect their scientific activity. (See appendix tables 6-55 and 6-56.) These trends roughly parallel those in R&D spending in the region (see chapter 2), especially in Russia, which experienced large decreases over the period.

Recent economic problems notwithstanding, Asia has emerged as a potent high-technology region.[68] Its output of scientific and technical articles in refereed journals grew rapidly over the past decade, providing evidence of a robustly developing indigenous S&E base. From 1986–88 to 1995–97, the Asian nations' world share of publications rose from 11 to 14 percent, amid contradictory trends. Japan's output rose 35 percent, while China's more than doubled; that of the four newly industrialized Southeast Asian economies—Taiwan, South Korea, Singapore, and Hong Kong—more than quadrupled, accounting for more than one-third of the continent's entire net increase. However, India's output continued to decrease, a matter of concern to that nation.[69] (See appendix tables 6-55 and 6-56.)

The conduct of research reflected in these article outputs requires financial, physical, and human resources. The empirical relationship between the size of a nation's

[65] Totals do not add because of rounding.

[66] Also see chapter 2, "U.S. and International Research and Development: Funds and Alliances"; chapter 4, "Higher Education in Science and Engineering"; and chapter 7, "Industry, Technology, and the Global Marketplace."

[67] These include five-year Framework Programmes of the European Union (EU), EU funding provided through Structural Funds, Community Initiatives Programmes, and efforts outside the EU framework such as EUREKA, a program to stimulate industry-university-research institutes partnerships. See NSF (1996b) for a brief discussion, European Commission (1997) for a fuller treatment.

[68] See NSF (1993 and 1995a). Also see chapter 2, "U.S. and International Research and Development: Funds and Alliances"; chapter 4, "Higher Education in Science and Engineering"; and chapter 7, "Industry, Technology, and the Global Marketplace."

[69] See Raghuram and Madhavi (1996). The authors note that this decline cannot be attributed to journal coverage in the SCI, and that it is paralleled by a decline in citations to Indian articles. They speculate that an aging scientific workforce may be implicated, along with a "brain drain" of young Indian scientists whose articles would be counted in the countries in which they reside, not in their country of origin.

economy—its gross domestic product (GDP)—and its article output volume is moderately high.[70] (See figure 6-34.) Clearly, however, some countries produce output well in excess of what would be expected, based on raw economic size. (See appendix table 6-57.) For example, Israel, the Nordic countries, Switzerland, and New Zealand rank particularly high; the United States is in the middle range. Nations with fast-developing economies tend to have smaller-than-expected article outputs, based on their estimated GDPs.

The Science and Technology Portfolios of Nations

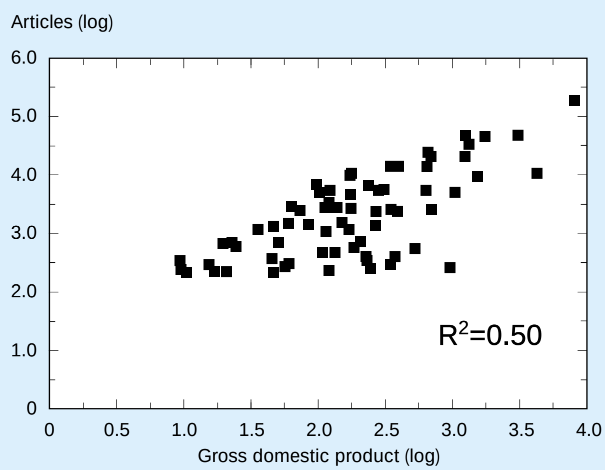
Nations make implicit or explicit choices about the nature of their science and technology portfolios through the allocation of resources; the results of these choices are roughly reflected in their article output data. It is clear that different nations have very different choice patterns, and also that these patterns can—and do—change over time.[71] (See appendix table 6-58.)

Figure 6-35 shows the 1995–97 portfolio mix of selected countries, arrayed by the fraction of their total output devoted to the life sciences (which account for about half of these articles worldwide). The differences in emphasis are striking. Europe's Nordic countries and many of Western Europe's smaller nations heavily emphasize the life sciences.

[70]The correlation of a nation's estimated GDP and number of articles in the ISI database produces an r^2 of 0.50. Because both GDP and number of articles are highly unevenly distributed, their logarithms have been used in this calculation.

[71]See also the discussion in chapter 4, "International Comparison of First University Degrees in S&E," on the field distributions of S&E degrees of various nations.

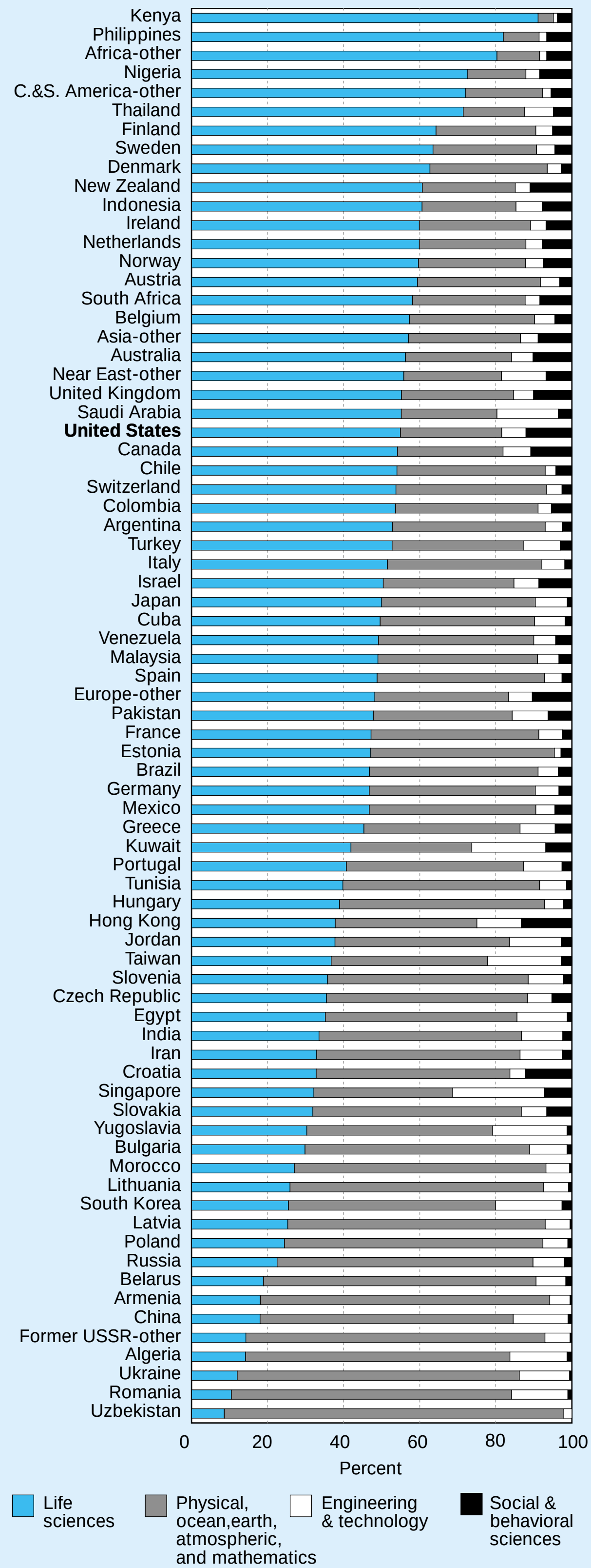
Figure 6-34.
Relationship of volume of scientific and technical articles to gross domestic product for selected countries: 1997



NOTE: Pearson correlation coefficient based on log-normalized article counts and gross domestic product.

See appendix table 6-57. *Science & Engineering Indicators – 2000*

Figure 6-35.
Distribution of selected countries' scientific and technical articles, by aggregated fields: 1995–97



See appendix table 6-58. *Science & Engineering Indicators – 2000*

China and Asia's newly industrializing economies emphasize the physical sciences and engineering and technology. The focus of Central and Eastern European nations and states of the former Soviet Union—reflecting historical patterns—rests heavily on the physical sciences. The world's biggest article-producing nations fall along a broad middle range: the United States, Canada, and the United Kingdom with slightly greater-than-average weight on the life sciences, Italy and Japan near the world average, and France and Germany weighted somewhat more toward the physical sciences. (See figure 6-35.)

Countries may shift the focus of their scientific activities. (See appendix table 6-59.) Since 1986–88, a large number of countries have increased their relative emphasis on physics while to some extent shrinking the shares of clinical medicine and, to a lesser extent, the other life sciences fields. Note that declining shares resulted sometimes, but not always, from falling absolute numbers of publications; in other instances, they reflected differential growth patterns. Perhaps not surprisingly, nations with long-established, large S&T systems exhibited greater stability in the field distribution of their articles than developing nations. Two things must be noted, however. First, the field designations used here are very broad, possibly obscuring larger changes even in the highly developed nations' portfolios. Second, moderate numerical shifts in low-volume countries' outputs can result in relatively large percentage changes across fields.

International Scientific Collaboration

Cutting-edge science in many fields increasingly involves a broad range of knowledge, perspectives, and techniques that extend beyond a given discipline or institution. This has generated increasing collaboration across disciplinary and institutional boundaries. Moreover, the scope, cost, and complexity of some of today's scientific problems (for example, mapping the human genome, constructing a coordinated array of widely spaced detection devices, or studying global environmental trends) invite—often even compel—international collaboration. In addition, developments in information technology reduce some of the geographic barriers to collaboration. For established scientific nations, this offers various benefits, including cost savings, the potential for faster progress, the application of different approaches to a problem, and the ability to stay abreast of information developed elsewhere. For nations with smaller or less-developed science and technology systems, it is a means of boosting the capabilities of their indigenous S&T base.

The past decade was marked by vigorous increases in international collaboration, as indicated by multicountry authors of scientific and technical articles. This phenomenon can be observed for every field and for most countries. From 1986–88 to 1995–97, the total number of articles in the ISI databases increased by 12 percent; coauthored papers rose by 46 percent (from an average of 177,100 to 258,500); and internationally coauthored articles increased by almost 115 percent (from 35,700 to 76,200). In 1995–97, half of the world's papers were coauthored (in the multi-institution sense), and 15 percent (30 percent of all coauthored articles) were written by international teams.[72] (See appendix table 6-60.) A web of intergovernmental agreements has developed that invites or requires multinational participation in some research activities. But the rise in international collaboration also appears to reflect the extent of advanced training students receive outside their native countries.[73] Figure 6-36 displays this relationship for the United States.

The incidence of coauthorship varied by field. In the United States in 1995–97, an average of 57 percent of all articles were coauthored. Clinical medicine was well above that with 66 percent; chemistry, engineering and technology, biology, mathematics, and the social and behavioral sciences had lower rates. (See appendix table 6-60.) Similar patterns are evident in many countries, suggesting field-specific publishing behaviors. In *international* collaboration, physics and earth and space sciences rank especially high; for some countries, mathematics also well exceeds the average, for others, biomedical research.

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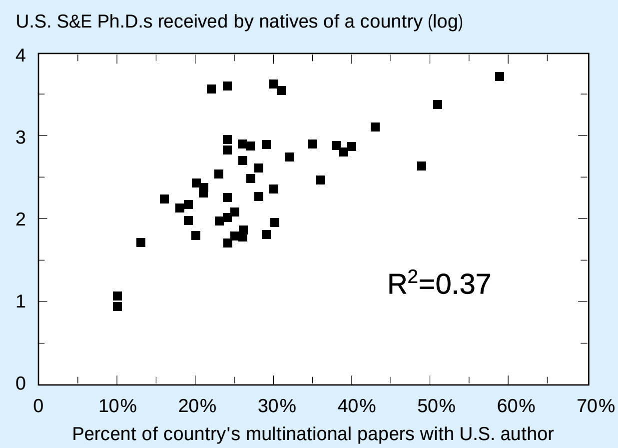
[72]The international coauthorship percentage for the world's papers appears low—15 percent—when compared to that of most individual countries, due to a counting artifact. *National* rates are based on total counts: each collaborating country is assigned one paper—that is, a paper with three international coauthors may contribute to the international coauthorship of three countries. However, for the world category, each internationally coauthored paper is counted only once. (In 1997, an average of 2.22 countries were involved in each internationally coauthored paper.)

[73]See chapter 4, "Higher Education in Science and Engineering."

Figure 6-36.
Relationship of volume of U.S.-coauthored multinational articles to U.S. S&E Ph.D.s received by natives of foreign authors' countries



NOTE: Articles published in 1991–95; Ph.D.s awarded in 1986–90.

SOURCES: Articles: Institute for Scientific Information, Science and Social Science Citation Indexes; CHI Research, Inc., Science Indicators database; and National Science Foundation, special tabulation. Ph.D.s: National Science Foundation, Survey of Earned Doctorates.

Science & Engineering Indicators – 2000

Who Collaborates With Whom?

Patterns of international coauthorship provide one indicator of the extent of collaborative ties among nations. By this indicator, the United States' position in international collaboration was characterized by two trends:

- From 1986–88 to 1995–97, most nations had increasing *numbers* of articles with at least one U.S. author.
- But the U.S. *share* of all their internationally coauthored articles declined.[74]

International scientific collaboration, as measured by the percentage of a country's multi-author articles involving international coauthorship, centers to a considerable degree on the United States. (See figure 6-37.) Worldwide, 44 percent of all internationally coauthored papers published in 1995–97 had at least one U.S. author. In that period, with few exceptions, from 25 to 33 percent of European countries' internationally coauthored papers involved collaboration with the United States.[75] For major science-producing Asian nations, coauthorship with U.S. researchers ranked higher. Japan and India—both nations with relatively low overall rates of international collaboration—shared 46 and 40 percent, respectively, of their internationally coauthored articles with United States researchers. Collaboration rates of other major article-producing Asian nations with the United States ranged from a high of 70 percent for Taiwan to a low of 31 percent for Singapore. China's rate was 33 percent (30 percent for Hong Kong)—but down sharply from 51 percent a decade earlier. For major South and Central American countries, rates ranged from 34 to 46 percent. The countries of Central Europe (except Hungary) and, especially, those of the former Soviet Union had lower rates of collaboration with the United States. (See appendix table 6-61.[76])

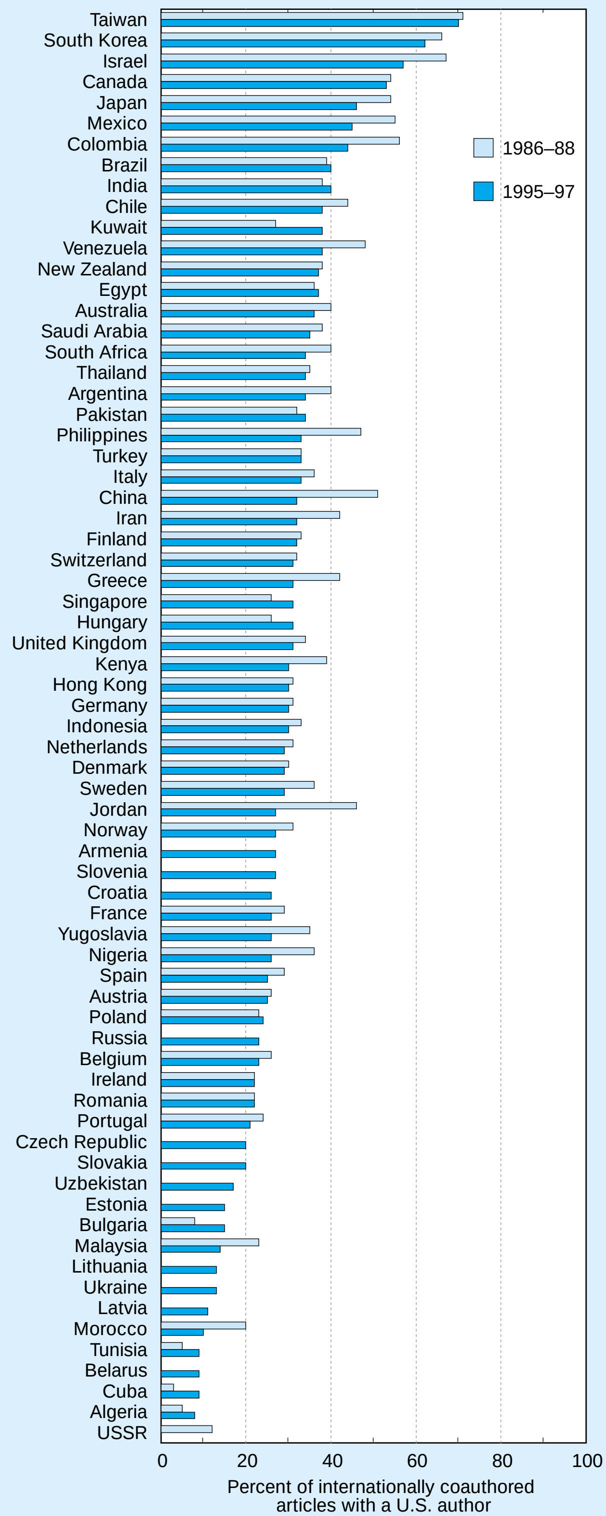
Comparison of these data with 1986–88 shows that, for most nations, the number of papers authored collaboratively with U.S. researchers rose strongly over the decade; however, the U.S. share of internationally coauthored articles declined from 51 to 44 percent of the world's total. This pattern—rising numbers of U.S. coauthored articles accompanied by declining U.S. shares—held for most countries, as they broadened the range of their international partnerships. In general, the higher the initial degree of collaboration with the United States, the greater the U.S. drop in collaboration share ($r^2 = 0.26$). Some examples (in percentage point terms): China, 19 percentage points; Israel and Mexico, 10 percentage points each; Japan, 8 percentage points; and 6 percentage points each for Chile and Argentina. (See appendix table 6-61.) These

[74]The first data column in appendix table 6-61 provides the percentages that U.S.-coauthored articles represent in a given country's internationally coauthored papers.

[75]These percentages are based on total article counts: a paper with one author each in two countries is counted as one article in each of the countries.

[76]The table is read as follows: The distribution of a given country's international collaborations with others is read along the rows. The prominence of a given country's coauthors in other countries' literatures is read down the columns.

Figure 6-37.
Percentage of internationally coauthored articles involving one or more U.S. authors for selected countries: 1986–88 and 1995–97



SOURCE: Institute for Scientific Information, Science and Social Science Citation Indexes; CHI Research, Inc., Science Indicators database; NSF, special tabulation

See appendix table 6-61. *Science & Engineering Indicators – 2000*

data suggest that new centers of activity and patterns of collaboration are evolving.

In the Asian region, the main trend indicates the development of regional collaborative patterns involving—especially—China and the newly industrialized economies. Overall, intraregional collaboration increased from 15 percent of all Asian foreign collaborations in the late 1980s to 24 percent a decade later. Regional collaboration rates—measured by the proportion of internationally coauthored articles published in 1986–88 and 1995–97 with an author from another Asian country—are shown in text table 6-7.

Text table 6-7 shows large increases in the overall number of articles, and of internationally coauthored articles, for a number of Asian countries, along with a rise in intra-Asian collaboration. For China, intra-Asian collaboration rose from 16 to 35 percent of its internationally coauthored papers (for Hong Kong from 25 to 47 percent) and for Singapore from 19 to 37 percent. However, regional collaboration remained relatively low for Japan, India, and Pakistan—12–15 percent of their internationally coauthored articles. Intra-Asian collaboration of Taiwan and South Korea—21 and 29 percent, respectively—was hardly changed since the mid-1980s.

Intraregional ties among the Central European states remain modest; in 1995–97 they shared 5 to 15 percent of their internationally coauthored articles. The bulk of their collaborations—roughly half for most nations—were with countries in the north, west, and south of Europe. Ties to the countries of the former USSR generally dwindled during the 1990s. Collaboration with U.S. scientists ranged from 14 to 27 percent and 31 percent for Hungary. (See appendix table 6-61.)

The collaborative ties of most countries of the former Soviet Union centered on Russia, Germany, and the United States. Almost one-half of Russia's coauthorships were with Germany and the United States, split evenly. Other major former constituent states—Ukraine, Belarus, Uzbekistan, and Armenia—shared 26–43 percent of their collaborations with Russia, and similarly large fractions with Germany and the United States combined. The Baltic nations have lower collaborative ties with Russia—11–17 percent. They have developed strong collaborative ties to the Nordic states, in particular to Finland and Sweden, reflecting the reestablishment of historical cultural and regional ties. (See appendix table 6-61.)

United States researchers partner with authors in a very large number of countries. In 1995–97, they collaborated with colleagues in more than 170 nations. German researchers were coauthors of 13 percent of U.S. internationally coauthored articles, and investigators from Canada and the United Kingdom of 12 percent each. Seven to 10 percent had authors from Japan, France, and Italy, respectively. The Netherlands, Switzerland, Israel, and Australia, with about 4 percent each, rounded out the top 10 collaborating nations.

The scope of different countries' collaborative ties with other nations can be seen in text table 6-8. It shows the total number of countries with any collaborating nondomestic author on a given nation's papers. The table reveals a dramatic expansion of cross-national collaboration over a mere decade. Virtually all countries expanded the number of nations with which they have some coauthorship ties, and a number of Asian nations more than doubled them.

Figure 6-38 shows the number of countries which shared at least one percent of their internationally coauthored articles with a given nation. The sharp drop-off in number of countries illustrates the practice of nations with relatively restricted S&T establishments to concentrate their collaborations in a relatively few countries. These smaller countries also tend to have higher levels of international coauthorship, as a percentage of their total article output, than do those with larger,

Text table 6-7.
Intra-Asian research collaboration—coauthorships among Asian countries: 1986–88 and 1995–97

	Number of articles		Internationally coauthored		Intra-Asia coauthored	
	1986–88	1995–97	1986–88	1995–97	1986-88	1995–97
	(sum)		(sum)		(sum)	
Japan	101,553	142,548	8,259	21,608	1,009	3,308
China	11,480	27,706	2,626	7,982	415	2,808
Hong Kong	1,518	6,741	333	2,694	83	1,253
South Korea	2,338	14,091	686	3,892	191	1,139
India	29,492	28,520	2,791	4,473	244	684
Taiwan	3,807	15,874	754	2,813	157	599
Singapore	1,344	3,874	318	1,147	62	423
Thailand	1,019	1,552	493	976	134	381
Indonesia	328	732	215	631	57	277
Malaysia	722	1,292	249	554	70	270
Philippines	542	695	247	454	96	219
Pakistan	695	998	237	420	22	49

NOTE: Internationally coauthored articles with authors from at least two Asian countries. Papers are counted in each author's country.

SOURCES: Institute for Scientific Information, Science Citation Index and Social Science Citation Index; CHI Research, Inc., Science Indicators database; and National Science Foundation, special tabulation.

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Text table 6-8.
Breadth of international coauthorship ties for selected countries: 1986–88 and 1995–97

Country	Number of countries 1986–88	Number of countries 1995–97	Country	Number of countries 1986–88	Number of countries 1995–97
United States	142	173	Malaysia	32	76
United Kingdom	121	163	Chile	42	76
France	116	157	Ireland	47	76
Germany	116	147	Philippines	44	75
Canada	101	136	Greece	47	75
Netherlands	88	133	Saudi Arabia	40	75
Switzerland	92	131	Colombia	32	72
Italy	94	128	Portugal	35	71
Belgium	81	128	Morocco	30	70
Sweden	90	127	Bulgaria	38	70
Japan	80	127	Romania	38	69
Australia	84	126	Taiwan	34	67
Spain	62	118	Singapore	42	65
Brazil	66	114	Venezuela	37	60
Denmark	73	111	Algeria	24	59
India	87	109	Kuwait	36	57
China	54	107	Cuba	29	56
South Africa	58	100	Pakistan	40	53
Austria	58	99	Iran	23	49
Israel	58	98	Tunisia	21	48
Norway	53	96	Jordan	22	46
Finland	58	94	Czechoslovakia	49	NA
Thailand	49	94	Czech Republic	na	90
Mexico	54	89	Slovakia	na	68
Hungary	54	89	USSR	61	NA
Poland	57	86	Russia	na	106
Turkey	31	85	Ukraine	na	70
Egypt	63	85	Belarus	na	55
Indonesia	39	84	Armenia	na	46
New Zealand	57	83	Lithuania	na	46
South Korea	33	83	Estonia	na	45
Hong Kong	35	82	Latvia	na	37
Kenya	52	81	Yugoslavia	56	60
Nigeria	57	77	Slovenia	na	67
Argentina	47	77	Croatia	na	58

NA = not applicable; na = not available

NOTE: Number of countries with which country indicated shares any coauthored articles. Countries of the former Soviet bloc and Yugoslavia shown at end of table.

SOURCES: Institute for Scientific Information, Science Citation and Social Science Citation Indexes; CHI Research, Inc., Science Indicators database; and National Science Foundation, special tabulations.

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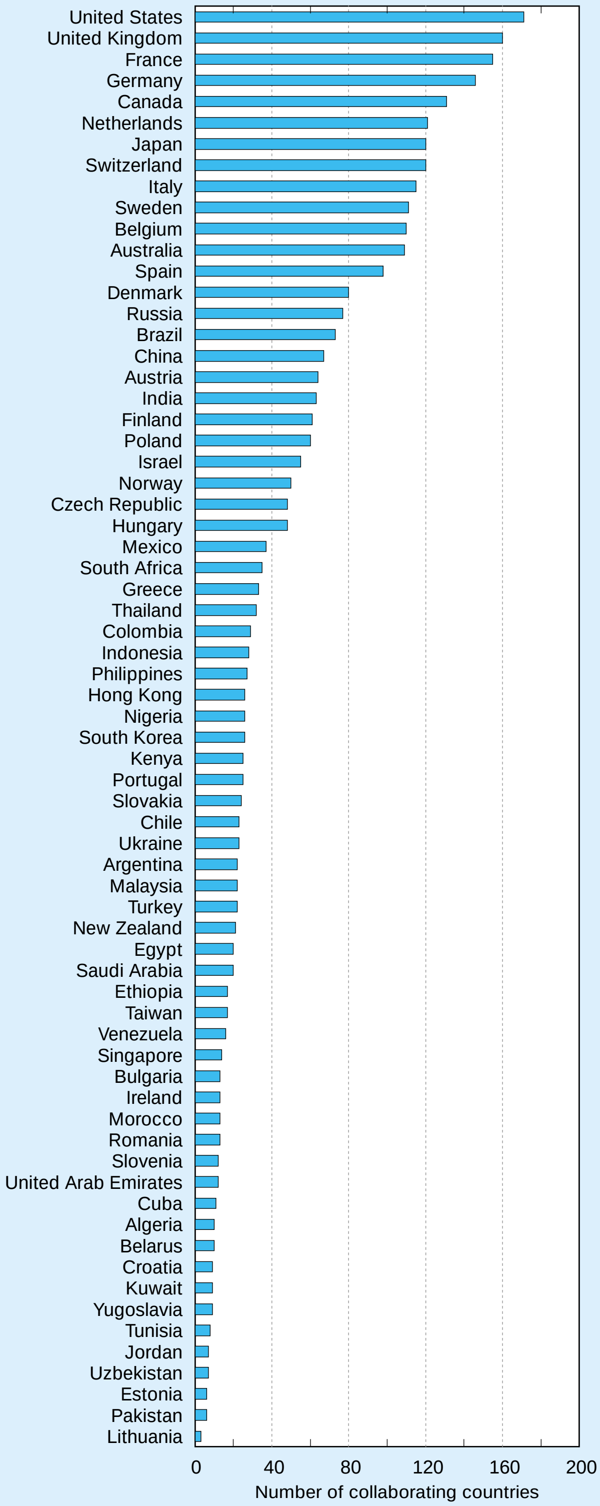
more mature systems. Rather than collaborating regionally, scientists from developing nations tend to work with those from major science-producing nations—in part based on student-mentor ties, as illustrated earlier by figure 6-36 for the United States.

International Citations to Scientific and Technical Articles

The global dimensions of the conduct of scientific activity, discussed above in terms of international research collaboration, are also reflected in the patterns of citations to the literature. Scientists and engineers around the world cite prior work done elsewhere to a considerable extent, thus acknowledging the usefulness of this output for their own work. Citations to one's own country's work are generally prominent and show less of a time lag than citations to foreign outputs. Regional citation patterns are evident as well, but citations to research outputs from around the world are extensive. Citations, aggregated here by country and field, thus provide an indicator of the perceived utility of a nation's science outputs in other countries' scientific and technical work. The discussion will cover:

- the high and rising proportion of citations to nondomestic publications; and
- the status of U.S. science—as indicated by citations to it—in the context of other countries' total citations to nondomestic articles.

Figure 6-38.
Number of countries which shared at least one percent of their internationally coauthored articles with nation indicated: 1995–97



SOURCE: Institute for Scientific Information, Science Citation Index; CHI Research, Science Indicators database; NSF, special tabulation.

See appendix table 6-61. *Science & Engineering Indicators – 2000*

The international nature of scientific research is underscored by the high volume of citations to work done abroad. Averaged across all countries and fields, close to 60 percent of all citations in 1997 were to foreign research. This average had stood at 53 percent only 7 years earlier, a rather rapid rate of change. The increases could be seen for most countries and most fields. The world averages include the relatively lower rate of foreign citations found in U.S. papers, which in turn reflects the very large U.S. share of total world article output. (See beginning of "International Article Production: Counts, Collaboration, and Citations," above.) Many other countries, especially those with small indigenous science establishments, cited foreign works with higher frequency than these averages would indicate. (See appendix table 6-62.)

Particularly high rates of foreign citations were found in physics, a field noted for its high rate of international collaboration. In contrast, foreign citation rates of articles in engineering and technology and the social and behavioral sciences were well below the average, reflecting greater reliance on domestic research. (See appendix table 6-62.)

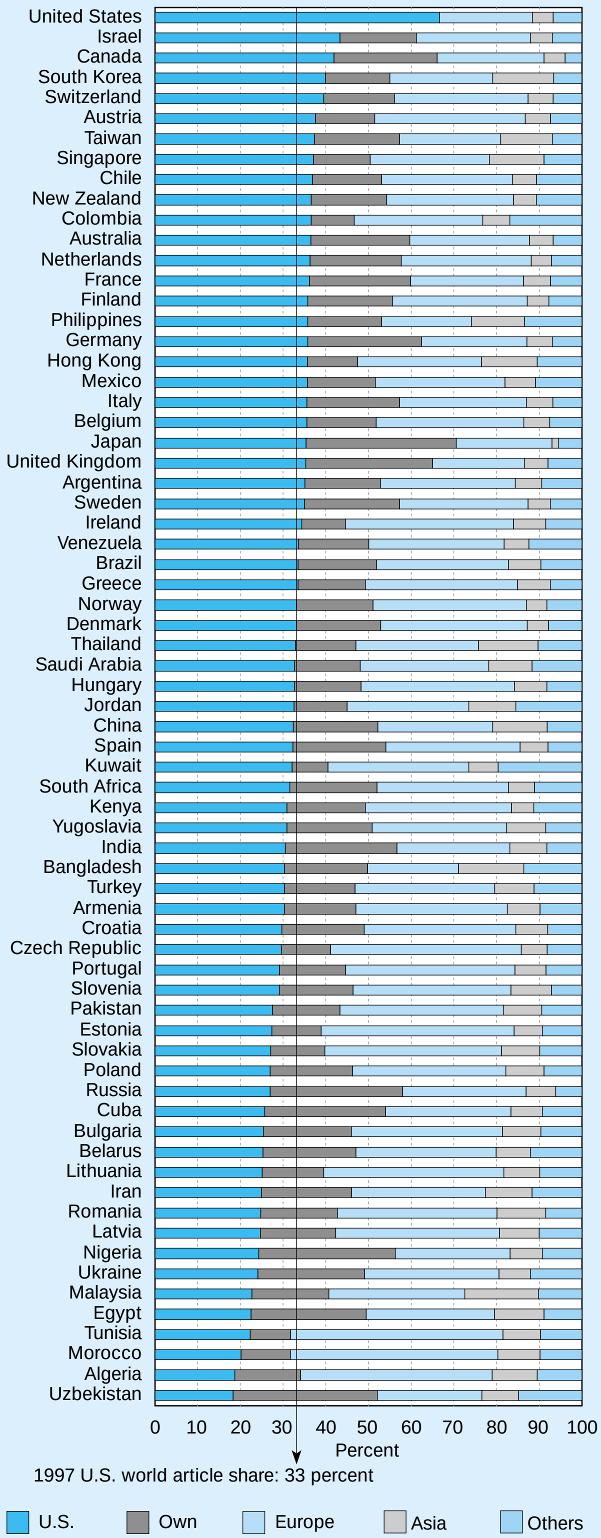
In a number of Asian countries, declines were registered in the share of citations to foreign sources overall. This was accompanied by a rise in citations to the scientific and technical literatures of other Asian nations. Intraregional citations increased from 6 percent of all references to nondomestic articles to 9 percent in less than a decade, from 1990 to 1997. As noted previously (see "Who Collaborates With Whom?" above), regional collaboration in Asia has been expanding over the period, from 13 percent to 18 percent of all Asian foreign collaborations. Seen in this light, these citation data point to continued growth of a more broad-based regional science capacity. (See appendix table 6-62.)

Citations to the U.S. literature in other nations' scientific and technical articles nearly always exceed the volume of citations to domestic research. (See Figure 6-39.) In most developed nations, such citations also run above the U.S. world article share. They drop below that mark for developing nations and for the former Soviet Bloc states, where access may be an issue.

Eliminating from consideration all countries' citations to their domestic articles adjusts for the well-documented tendency to favor domestic literature.[77] From the menu of available world science (not their own), to what extent do researchers in these nations select U.S. articles to read and cite? The proportion of U.S. articles among all citations to nondomestic literatures is very high and in most instances exceeds the U.S. share of world articles. (See figure 6-40.) For example, the U.S. article share in physics has declined from 28 to 22 percent since 1990, and the citations share (the average in all other countries' nondomestic citations) has dropped from 49 to 39 percent over the same period. (See text table 6-9.) However, after an approximate allowance is

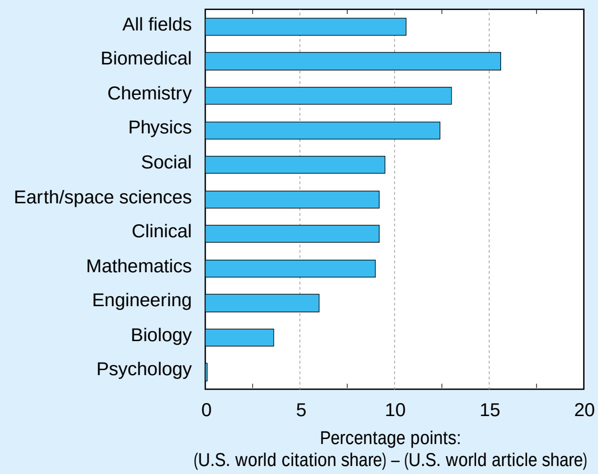
[77]After summing all countries' (except the United States') citations to nondomestic articles and calculating what percentage of these refer to U.S. articles, this percentage is compared to the U.S. world article share.

Figure 6-39.
Citations in selected countries' scientific and technical literature to U.S., own, and major regions' articles: 1997



See appendix table 6-61. *Science & Engineering Indicators – 2000*

Figure 6-40.
Citations to U.S. research in other nations' scientific and technical articles, relative to U.S. world article shares, by field



NOTE: Plotted values are the difference between the 1993 U.S. share of the world literature and the 1997 U.S. share of other nations' citations to foreign literature. For example, foreign citations to U.S. mathematics articles are about 9 percentage points higher than would be expected on the basis of the U.S. article share in the field.

SOURCE: Institute for Scientific Information, Science and Social Science Citation Indexes; CHI Research, Inc., Science Indicators database; NSF, special tabulation.

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made for time lags between publication and citation—here by comparing the 1997 citations share (39 percent) with the 1993 article share (27 percent)—U.S. physics articles remain cited well above the share expected based on article volume alone. (See appendix table 6-63.)

Citations on U.S. Patents to the Scientific and Technical Literature

Patent applications cite "prior art" that contributes materially to the product or process to be patented. Citations to such prior art have traditionally been to other patents; increasingly, these citations include scientific and technical articles. The percentage of U.S. patents which cited at least one such article increased from 11 percent in 1985 to 14 percent in 1990 and 25 percent in 1996.[78] This development attests to both the growing closeness of some research areas to practical applications and an increasing willingness of the U.S. Patent and Trademark Office (PTO) to award upstream patents. Thus, citations of scientific and technical articles on patents provide a good indicator of the growing linkage between research and innovative application, as judged by the patent applicant and recognized by PTO.[79]

[78]Personal communication with Francis Narin, CHI Research, Inc., and National Science Board (1998).

Text table 6-9.
Citations to foreign articles in the world's major scientific and technical journals, by field: 1990–97

Field	Citations to foreign articles (percent)			Citations to U.S. articles (percent of foreign citations)			U.S. share of articles (percent of world total)		
	1990	1993	1997	1990	1993	1997	1990	1993	1997
All fields	53	56	59	52	50	47	37	36	33
Physics	58	63	64	49	44	39	28	27	22
Chemistry	54	57	60	40	39	36	22	23	20
Earth/space sciences	52	54	58	53	51	49	39	40	36
Mathematics	50	53	56	50	50	47	41	38	32
Biology	50	53	57	42	42	37	37	33	30
Biomedical research	54	57	59	57	56	55	39	39	38
Clinical medicine	55	57	61	52	50	48	39	39	36
Engineering/technology	47	51	55	48	46	40	38	34	29
Psychology	37	38	42	66	63	58	60	58	55
Social sciences	33	35	40	66	64	62	55	53	49
Health/professional fields	23	25	31	71	68	65	70	69	63

NOTES: Citations are for a three-year period with a two-year lag; for example, 1997 citations are to 1993–95 articles. Foreign citations exclude those in U.S. journals.

SOURCES: Institute for Scientific Information, Science Citation and Social Science Citation Indexes; CHI Research, Inc., Science Indicators database; and National Science Foundation, special tabulation. *Science & Engineering Indicators – 2000*

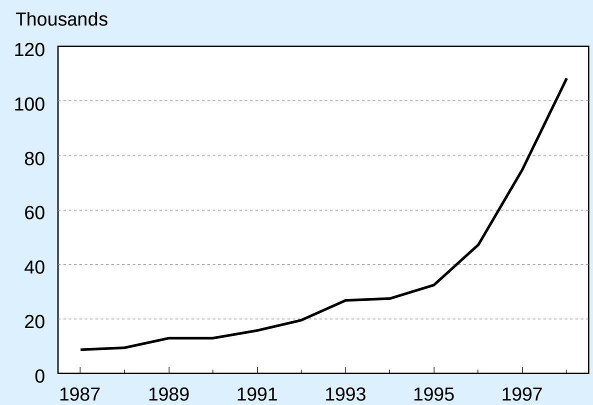
Citations to U.S. research articles included in the SCI set of journals were identified and classified by field and performer sector for all U.S. patents issued from 1987 through 1998. The number of such citations stood at 8,600 in 1987, more than doubled over five years, doubled again in less than four years (1996: 47,000), then doubled again in less than two years to reach 108,300 in 1998.[80] (See figure 6-41 and text table 6-10.) The rise in the number of citations held for all fields and for papers from all sectors. (See appendix table 6-64.)

The explosive growth of article citations on patents was rooted in enormous increases in the life sciences: from 2,400 to 55,900 in biomedical research in little more than a decade, and from 2,200 to 33,400 in clinical medicine. Consequently, even as the number of citations increased to articles in every field, the field shares shifted dramatically:

- Biomedical research rose from 28 percent in 1987 to 52 percent in 1998; clinical medicine from 26 to 31 percent.
- The combined share of physics, chemistry, and engineering and technology citations dropped from 43 to 15 percent.

Patent citations to academic articles rose faster than citations to industry or government authors, pushing the academic share of the total from 48 to 54 percent from 1987 to 1998. The academic sector's share of all article citations on patents increased particularly strongly in physics (from 29 to 41 percent), earth and space sciences (40 to 56 percent), and engineering and technology (26 to 46 percent)—fields with stagnating or declining industry article output. (See appendix tables 6-64 and 6-65.)

Figure 6-41.
Number of citations on U.S. patents to scientific and technical articles: 1987–98



NOTE: Changed U.S. Patent and Trademark Office procedures, greater ease of locating scientific and technical articles, and greater incentive to cite them may have contributed to some of these increases.

SOURCE: CHI Research, Inc. Science Indicators and Patent Citations databases; NSF, special tabulation.

See appendix table 6-64. *Science & Engineering Indicators – 2000*

[79]Some caveats apply. The use of patenting varies by industry segment, and many citations on patent applications are to prior patents. Industrial patenting is only one way of seeking to ensure firms' ability to appropriate returns to innovation and thus reflects, in part, strategic and tactical decisions, for example, laying the groundwork for cross-licensing arrangements. Most patents do not cover specific marketable products but might conceivably contribute in some fashion to one or more such products in the future.

[80]Some of the rise may reflect changed U.S. Patent and Trademark Office procedures, greater ease of locating the relevant prior art, and greater incentives to include all possible elements thereof. Nevertheless, the direction and strength of the trends reported here are congruent with those in academic patenting, discussed below. The number of citations reported here refer to articles published in a 12-year span, as follows: 1997 patent citations are to articles published in 1983 to 1994, and so forth.

Text table 6-10.
Number and distribution of citations on U.S. patents to the U.S. scientific and technical literature, by field

Citation year	Total	Physics	Chemistry	Earth & space	Mathe-matics	Clinical medicine	Biomedical research	Biology	Engineering & technology	All others
Number of citations										
1987	8,618	1,286	1,181	105	0	2,221	2,390	168	1,242	23
1988	9,498	1,595	1,212	81	2	2,423	2,749	220	1,209	5
1989	12,988	2,356	1,536	119	2	3,190	3,976	304	1,458	44
1990	12,936	2,169	1,673	76	3	3,415	3,818	306	1,443	31
1991	15,720	2,424	1,921	123	2	4,205	5,199	437	1,401	4
1992	19,425	2,667	2,451	94	18	5,293	6,945	436	1,492	26
1993	26,721	3,024	3,027	93	21	7,393	10,735	548	1,850	26
1994	27,437	3,589	3,114	122	14	7,215	10,332	677	2,346	25
1995	32,536	3,366	3,689	134	19	9,173	12,719	812	2,593	27
1996	47,142	3,506	4,535	195	25	13,637	20,646	1,349	3,207	36
1997	74,839	4,150	6,218	207	30	22,649	36,397	1,508	3,589	85
1998	108,335	4,719	6,900	285	35	33,437	55,891	2,426	4,452	189
Percent of citations										
1987	100	14.9	13.7	1.2	0.0	25.8	27.7	1.9	14.4	0.3
1988	100	16.8	12.8	0.9	0.0	25.5	28.9	2.3	12.7	0.1
1989	100	18.1	11.8	0.9	0.0	24.6	30.6	2.3	11.2	0.3
1990	100	16.8	12.9	0.6	0.0	26.4	29.5	2.4	11.2	0.2
1991	100	15.4	12.2	0.8	0.0	26.7	33.1	2.8	8.9	0.0
1992	100	13.7	12.6	0.5	0.1	27.2	35.8	2.2	7.7	0.1
1993	100	11.3	11.3	0.3	0.1	27.7	40.2	2.1	6.9	0.1
1994	100	13.1	11.3	0.4	0.1	26.3	37.7	2.5	8.6	0.1
1995	100	10.3	11.3	0.4	0.1	28.2	39.1	2.5	8.0	0.1
1996	100	7.4	9.6	0.4	0.1	28.9	43.8	2.9	6.8	0.1
1997	100	5.5	8.3	0.3	0.0	30.3	48.6	2.0	4.8	0.1
1998	100	4.4	6.4	0.3	0.0	30.9	51.6	2.2	4.1	0.2

NOTE: Count for 1987 patents is of citations to articles published in 1973-84; for 1988 patents to articles published in 1974-85; and so forth.

SOURCES: Institute for Scientific Information's Science Citation and Social Science Citation Indexes; CHI Research, Inc., Science Indicators database; and National Science Foundation, special tabulation.

See appendix table 6-64. *Science & Engineering Indicators – 2000*

Examination of the sectoral patterns of patent citations reveals the prominent and growing role of biomedical research in the cited articles from every sector (ranging from 44 to 59 percent of all article citations), accompanied by strong or growing citation of papers in clinical medicine. (See appendix table 6-66.) The composition of citations to academic and industry articles, in particular, illustrates the key role of these areas of inquiry: Only 10 percent of citations to industry articles referred to physics, down from 29 percent a decade earlier. But 71 percent of patent citations to industry articles were to the life sciences, up from less than a quarter.

Further exploration of these trends was undertaken by Narin, Hamilton, and Olivastro.[81] Their study examined the citations on the front sheets of all 397,660 U.S. patents awarded in 1987–88 and 1993–94. While many citations were to other patents, about 430,000 referred to nonpatent materials; 242,000 were judged to be science references. In addition to the rapid increase in article citations on U.S. patents, the authors discovered a shortening interval between publication and citation and a large proportion of citations to publicly funded science (defined by the authors to include articles by academic, nonprofit, and government authors).[82] References tended to be to articles appearing in nationally and internationally recognized, peer-reviewed journals, including journals publishing basic research results, and to be field- and technology-specific.[83] The authors noted both national (U.S. patents citing U.S. authors with greater-than-expected frequency) and regional components in the patterns of citations.

Academic Patenting: Patent Awards, Licenses, Startups, and Revenue

Governments assign property rights to inventors in the form of patents to foster inventive activity that may have important economic benefits. The U.S. Patent and Trademark Office (PTO) grants such government-sanctioned property rights in the form of patents for inventions deemed to be new, useful, and non-obvious. This section discusses recent trends in academic patenting and income from these activities flowing to universities and colleges.[84]

[81]Narin, Hamilton, and Olivastro (1997).

[82]This latter finding is broadly consistent with results obtained by Mansfield (1991), focusing on academic science only and using a very different study framework and approach.

[83]See tables 2 and 3 in Narin, Hamilton, and Olivastro (1997).

Trends in academic patenting provide an indication of the importance of academic research to economic activity, which may well be growing even in the short term. The bulk of academic R&D is basic research, that is, not undertaken to yield or contribute to immediate practical applications. However, academic patenting data show that universities are giving increased attention to potential economic benefits inherent in even their most basic research—and that the U.S. PTO grants patents based on such basic work, especially in the life sciences.

A growing number of academic institutions are applying for, and receiving, protection for results of work conducted under their auspices. After slow growth in the 1970s, the number of academic institutions receiving patents increased rapidly in the 1980s from about 75 early in the decade to double that by 1989 and nearly 175 by 1997. This development, pronounced during the 1980s and more muted in this decade, reflected increases in the number of both public and private institutions receiving patents.[85] (See figure 6-42 and appendix table 6-67.)

Starting in the early 1980s, the number of institutions outside the ranks of the largest research universities (defined here as the top 100 in total R&D expenditures) with patent awards increased at a rapid pace. The Nation's largest research universities represented 64 percent of all academic institutions receiving patents in 1985; their number had fallen to half by 1996.[86] Much of the broadening of the base of patenting institutions occurred among public universities and colleges. (See appendix table 6-67.)

Increasing university patenting and collaboration with industry have given rise to questions about possible unintended consequences—for universities and academic researchers—arising from these developments. Concerns have been expressed about potential distortions of the nature and direction of academic basic research, about contract clauses specifying delays or limitations in the publication of research results, and about the possibility of the suppression of research results for commercial gain. Unsettled questions also arise from faculty members' potentially conflicting economic and professional incentives in such arrangements. Universities as institutions may find themselves in a similarly ambiguous position as they acquire equity interests in commercial enterprises. In addition, scholars have asked whether patenting of government-sponsored research results may not in fact be detrimental to its intended goal of enhancing the transfer of new technologies.[87] These unsettled questions provide the backdrop for the rapidly rising numbers of academic patents.

The expansion of the number of institutions receiving patents coincided with rapid growth in the number of patent awards to academia, which rose from 589 in 1985 to 3,151 in 1998, accelerating rapidly since 1995. By the mid-1980s, the share of patents accounted for by the top 100 R&D-performing universities was about 77 percent of the total, as academic institutions started responding to provisions of the Bayh-Dole Act of 1980.[88] However, since the late 1980s, these large research universities have accounted for over 80 percent of all academic patents, a figure which increased to 89 percent by 1998. (See appendix table 6-67.)

The number of academic patents has risen tenfold, from about 250 annually in the early 1970s to more than 3,100 in 1998 (see figure 6-43), a far more rapid increase than for all annual U.S. patent awards. As a result, academic patents now approach 5 percent of all new U.S-origin patent awards, up from less than one-half of 1 percent two decades ago. The Bayh-Dole Act may have contributed to the strong rise in the 1980s, although university patenting was already on the rise before then. The creation of university technology transfer and patenting units, an increased focus on commercially relevant technologies, and closer ties between research and technological development may have contributed as well. A landmark Supreme Court ruling (Diamond v. Chakrabarty) allowing patentability of genetically-modified life forms may have been a

[84]Chapter 7 presents a more comprehensive discussion of patented inventions in all U.S. sectors.

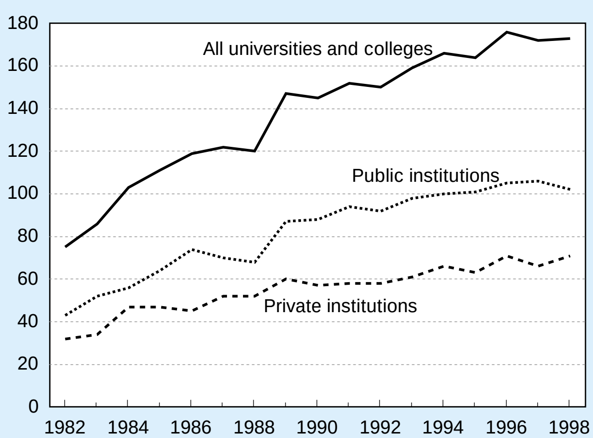
[85]Exact counts are difficult to obtain. Patent assignment depends on university practices which vary and can change with time. Patent assignment may be to boards of regents, individual campuses, subcampus organizations, or entities with or without affiliation with the university. The data presented here have been aggregated consistently by the U.S. Patent and Trademark Office starting in 1982. The institution count is conservative, since a number of university systems are included in the count and medical schools are often counted with their home institutions.

[86]These estimates are understated, since patent awards to some universities—for example, University of California, State University of New York—are generally recorded at the system level. But the trend reported here is calculated on a consistent basis.

[87]See Mazzoleni and Nelson (1998) and Ganz-Brown (1999).

[88]The Bayh-Dole University and Small Business Patent Act of 1980 permitted government grantees and contractors to retain title to inventions resulting from federally supported R&D and encouraged the licensing of such inventions to industry. Several empirical studies have recently examined effects of this law. See Henderson, Jaffe, and Trajtenberg (1998); and Mowery, Nelson, Sampart, and Ziedonis (in press)(2000).

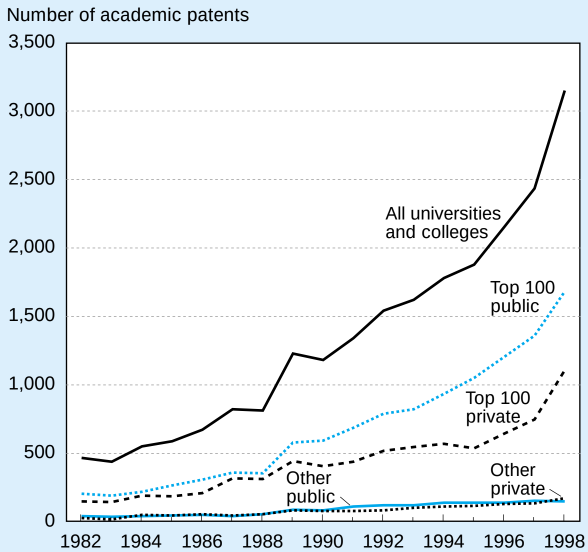
Figure 6-42.
Number of universities and colleges granted patents: 1982–98



NOTE: Numbers are lower-bound estimates because of some systemwide reporting.

See appendix table 6-67. *Science & Engineering Indicators – 2000*

Figure 6-43.
Number of academic patents granted: 1982–98



NOTE: The top 100 universities are defined as the institutions reporting the largest total R&D expenditures for 1997. Details do not add to total because of omission in detailed tally of academic patents held by unaffiliated agencies.

See appendix table 6-67. *Science & Engineering Indicators – 2000*

prime stimulus for the recent rapid increases, leading to greater PTO readiness to patent certain basic research outputs.

What is clear is that the vigorous increases in the number of academic patents largely reflect developments in the life sciences and biotechnology.[89] Two key trends in academic patenting are worth noting. First, a heavy concentration is evident in areas connected with the life sciences. Patents in a mere three technology areas or "utility classes"—all with presumed biomedical relevance[90]—accounted for 41 percent of the academic total, up from a mere 13 percent through 1980. (See figure 6-44.) Second, the growth in the number of academic patents was accompanied by a decrease in the number of utility classes in which they fall. In fact, academic patents are concentrated in far fewer application areas than are all U.S. patents. (See appendix table 6-68.)

Valuation of patents—especially of science-based ones—is difficult, and there are no guarantees that patents will have any direct economic value. Nevertheless, the motivation behind academic patenting is to protect intellectual property that is deemed valuable by the university, and academic institutions are increasingly successful in negotiating royalty and licensing arrangements based on their patents. While total reported revenue flows from such licensing arrangements remain low, compared to R&D spending, a strong upward trend points to the confluence of two developments: a growing eagerness of universities to exploit the economic potential of research activities conducted under their auspices, and readiness of entrepreneurs and companies to recognize and invest in the market potential of this research.

A 1992 survey by the U.S. General Accounting Office based on 35 universities found that they had substantially expanded their technology transfer programs during the 1980s. Typical licensees were small U.S. pharmaceutical, biotechnology, and medical businesses. During 1989–90, the reported income flows from these licenses were a mere $82 million. A more extensive survey has been conducted periodically since 1991 by the Association of University Technology Managers (AUTM).[91] The survey initially included only 98 universities, but has been augmented since 1993, with the additional institutions representing a coverage increase from 75 to 82 percent of academic R&D funds, from 85 to 90 percent of Federal academic R&D support, and from 80 to 91 percent of patents issued to academic institutions. (See text table 6-11.)

All indicators shown in this table point to an accelerating use of patenting by the Nation's universities and colleges. The number of new patents, license disclosures, applications filed, startup firms formed, and base of revenue-generating licenses and options are all growing at rapid rates, especially in the last two years shown. Key points are:

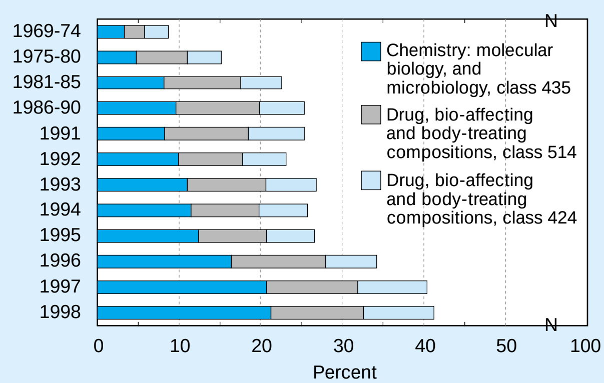
- University income from patenting and licenses is increasing steeply, reaching $483 million in 1997, although relative to academic research expenditures it remains low.
- About half of total royalties were classified by respondents as being related directly to the life sciences; about one-third was not classified by field; the remainder, labeled "physical sciences," appears to include engineering.

[89]See Huttner (1999).

[90]Utility classes numbers 424 and 514 capture different aspects of "Drug, bio-affecting and body treating compositions"; utility class number 435 is "Chemistry: molecular biology and microbiology." Patents are classified here according to their primary technology class.

[91]Association of University Technology Managers, Inc. (1998).

Figure 6-44.
Percentage of total academic patents in three largest academic utility classes: 1969–98, selected years



SOURCE: U.S. Department of Commerce, Patent and Trademark Office, Technology Assessment and Forecast Report, U.S. Universities and Colleges, 1969-98; NSF, special tabulation.

See appendix table 6-68. *Science & Engineering Indicators – 2000*

Text table 6-11.
Academic patenting and licensing activities

	1991	1992	1993	1994	1995	1996	1997
Finances (millions of dollars)							
Gross royalties	$130.0	$172.4	$242.3	$265.9	$299.1	$365.2	$482.9
New research funding from licenses	NA	NA	NA	$106.3	$112.5	$155.7	$136.2
Royalties paid to others	NA	NA	$19.5	$20.8	$25.6	$28.6	$36.2
Unreimbursed legal fees expended	$19.3	$22.2	$27.8	$27.7	$34.4	$46.5	$55.5
Invention disclosures, patent applications, patents							
Invention disclosures received	4,880	5,700	6,598	6,697	7,427	8,119	9,051
New patent applications filed	1,335	1,608	1,993	2,015	2,373	2,734	3,644
Total new patents received	NA	NA	1,307	1,596	1,550	1,776	2,239
Licenses, options, startup companies							
Startup companies formed	NA	NA	NA	175	169	184	258
Number of revenue-generating licenses, options	2,210	2,809	3,413	3,560	4,272	4,958	5,659
New licenses and options executed	1,079	1,461	1,737	2,049	2,142	2,209	2,707
Equity licenses and options	NA	NA	NA	NA	99	113	203
Survey coverage							
Number of institutions responding	98	98	117	120	127	131	132
Percent of total academic R&D represented	65	68	75	76	78	81	82
Percent of federally funded academic R&D represented	79	82	85	85	85	89	90
Percent of academic patents represented	NA	NA	80	89	82	82	91

NA = not available

NOTE: New research funding from licenses is defined as research funds directly related to signing of a specific license agreement.

SOURCE: Association of University Technology Managers, Inc. (AUTM), *AUTM Licensing Survey, Fiscal Year 1991–Fiscal Year 1997* (Norwalk, CT: 1998).

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- The number of startups and of licenses and options granted increased strongly. Forty-one percent of new licenses and options went to large firms, 48 percent to small existing companies, and 11 percent to startups.

Conclusion

Over the past decade, the academic research and development enterprise has enjoyed strong growth. It continues to perform approximately half of U.S. basic research and is a major contributor to the nation's and the world's stock of scientific knowledge. Such knowledge appears to be increasingly tied to economic benefits. In turn, an increasingly technologically oriented economy is likely to place a premium on highly educated workers. Nevertheless, U.S. higher education is facing a number of challenges, some arising from within science and engineering, others from changes in the academic environment.

Higher education's overall financial environment has improved somewhat when compared to the recession years at the decade's turn, when many state governments combined flat or reduced appropriations with new accountability measures. Years of steep and unpopular increases in tuition and fees appear to lie in the past as well. Nevertheless, the Nation's universities and colleges continue to face cost pressures, even as nontraditional providers of teaching and training try to capture a growing share of traditional academic markets.

For many of the largest universities, a major uncertainty arises from the restructuring of the Nation's health care system. Some have responded by making structural changes in the relationships with their teaching hospitals, including one of turning them into for-profit ventures. Federal reimbursement changes are feared by many to have adverse effects on biomedical and clinical research and teaching.

For support of their R&D, academic institutions continue to rely heavily on the Federal Government, thus maintaining a certain dependence on implicit Federal priorities for the funding balance among fields. Universities' own resources are approaching one-fifth of their total R&D expenditures. However, in the face of financial pressures on all academic operations, this funding source cannot be expected to continue growing as a share of total academic R&D resources. Industry is often viewed as a potentially growing support source but has continued to supply less than 10 percent of the total funds, even as it has increasingly relied on academic R&D.

Demographic projections point to strong enrollment growth over the next decade and the continuation of several trends: more minority participation, growing numbers of older students, and greater proportions of non-traditional students. Issues of access, affordability, and fairness are likely to mix with considerations of institutional focus, mission, and strategy. Financial and other pressures will be part of the context in which they will unfold; undoubtedly, so will new service possibilities offered by technological developments, which carry their own costs and challenges.